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What is the most adequate method to assess thermal comfort in hybrid commercial buildings located in hot-humid summer climate?

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ABSTRACT

The aim of this paper is to identify which method to assess thermal comfort is the most appropriate to be used in hybrid commercial buildings located in hot and humid summer climate. Three methods to assess thermal comfort were analysed: (1) ASHRAE 55 for determining acceptable thermal conditions in occupied spaces, (2) ASHRAE 55 for determining acceptable thermal conditions in naturally ventilated spaces and (3) Givoni's chart for hot and humid climates. Models with two geometries, two room sizes per geometry, two solar orientations and three window areas per model were analysed. Simulations were performed using the EnergyPlus programme, with the TRY climate file of Florianópolis. Thermal comfort was evaluated applying the simulations output data into the three methods. Thus, the amount of time (number of hours per year) in which the use of air-conditioning is necessary to bring thermal comfort for the users throughout the year was determined using each method. Such number of hours of use of air-conditioning was also compared with the pattern of use of air-conditioning observed in Florianópolis. The main conclusion is that the most suitable method for use in hot and humid summer climates is the method proposed by Givoni.

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1. Introduction

Natural ventilation systems are being increasingly incorporated into buildings in order to reduce the thermal heat load and consequently the energy consumption due to air-conditioning systems. Buildings are a heat source, mainly in summer conditions. Thus, the use of natural ventilation is very efficient to remove part of such thermal load from the buildings [1]. In subtropical climates, the use of natural ventilation in buildings has a great potential for energy savings because this type of climate is characterised by mild winters and outdoor temperatures lower than indoor temperatures in most of the year [2].

The natural ventilation obtained from façade openings is limited to some climates, locations and building typologies, but it can be extended to hybrid buildings, also known as mixed-mode buildings (from now on, only the term hybrid buildings will be used in this work). In hybrid buildings there is the integration between natural ventilation and mechanical system (which can be used to improve the air distribution and chill the air) [3,4]. Hybrid systems provide a comfortable indoor environment through natural and mechanical systems which are activated depending on outdoor environment conditions in different times of the day and/or seasons. It aims to maximise comfort while minimising the energy consumption and operation costs of air-conditioning [5].

In general, hybrid buildings present an energy consumption lower than air-conditioned buildings. Researches showing a good performance of hybrid ventilation systems were carried out by [5–11]. Although, many authors [12–21] have been studying thermal comfort in commercial buildings with air-conditioning or natural ventilation (and defining methods to evaluate thermal comfort in such buildings), in hybrid ventilated buildings the choice for a method to assess thermal comfort is still in discussion. De Dear and Brager [21] suggested that the method for determining acceptable thermal conditions in naturally ventilated spaces from ASHRAE Standard 55 [22] could be used in buildings operating with hybrid ventilation. When the interior temperatures are within the limits of acceptability of such standard the building operates with natural ventilation; the air-conditioning is used to guarantee temperatures within the acceptability limits, when the maximum limits of acceptability are reached [21].

Mankibi et al. [6] studied a room located in Copenhagen (Denmark), equipped first with a natural ventilation system and subsequently with a mechanical system. Two reference mechanical systems (one with heat recovery) and a hybrid ventilation system were analysed. The simulations were performed using two programmes, i.e., SPARK and HYBCELL1.0, considering air flow, heat transfer and CO_2 concentration. The pattern of opening windows was based on the temperature, which was considered as a parameter of thermal comfort. The authors concluded that in winter and spring the hybrid ventilation system consumed more energy (the difference was more significant in winter). However, the levels of CO_2 concentration were lower than in mechanical systems. In summer, the hybrid system consumed much less energy than the mechanical system, but the CO_2 concentrations were a little higher than the reference systems.

Jreijiry et al. [7] considered the operative temperature as a parameter of thermal comfort. They studied hybrid ventilation systems in residential buildings. A mechanical system (reference) and a hybrid ventilation system (operating with two control strategies: presence of occupants and CO_2 concentration) were modelled. A single family house located in four European cities was simulated: Trappes (France), Stockholm (Sweden), Athens (Greece) e Nice (France), including temperate (Trappes), cold (Stockholm) and hot (Athens e Nice) climates. The SIMBAD Building and HVAC Toolbox programmes were used. The indoor air quality, thermal comfort, energy consumption and stability of control strategies were considered in the analysis. Results showed that the hybrid ventilation system improved the indoor air quality, reduced the fan consumption and maintained the same consumption for heating, when compared to the reference system.

A more detailed analysis of comfort was performed by Kim and Hwang [8], who studied the performance of a hybrid ventilation system in a building located in Seoul (South Korea). The hybrid system was composed of a natural supply inlet and mechanic exhaust. The analysis was performed using Computational Fluid Dynamics (CFD) for ventilating flow rates of 30, 60 and 120 m^3/h. Thermal comfort was evaluated considering operative temperature, air velocity and vertical temperature gradient. Results indicated that the ventilating flow rate of 60 m^3/h satisfied the comfort criteria, while the other two ventilating flow rates did not attend the criteria for temperature and air velocity established by the authors.

Brager and Baker [5] compared the environment performance data (thermal comfort, air quality, acoustics, lighting, cleanliness, spatial layout, and office furnishings) of 12 hybrid commercial buildings with the data of 358 air-conditioned commercial buildings. The data are from a database created by the Center for the Built Environment, University of California. These data were obtained through assessments of occupant satisfaction with their workspace. The assessments were performed through satisfaction questions using a 7-point scale ranging from very satisfied (+3) to very dissatisfied (−3), with a neutral midpoint (0). The authors concluded that, on average, the performance of hybrid buildings

Table 1
Latitude, longitude and altitude of Florianópolis.

City	Latitude	Longitude	Altitude
Florianópolis (Brazil)	−27°36′	−48°33′	7 m

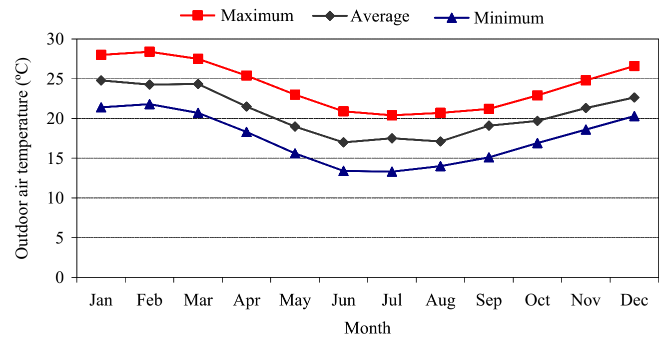

Fig. 1. Maximum, minimum [23] and average [24] outdoor air temperature throughout the year in Florianópolis.

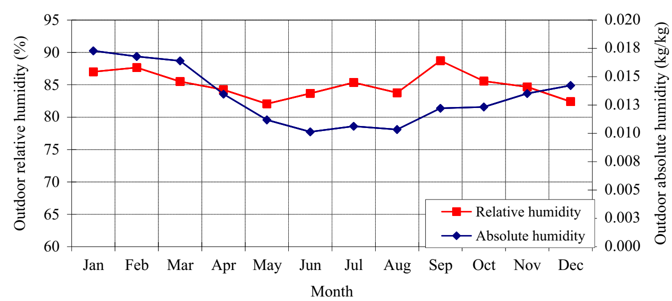

Fig. 2. Average outdoor air relative humidity and average outdoor air absolute humidity throughout the year in Florianópolis.
Source: based on Brasil [23].

(especially concerning thermal comfort and air quality) is significantly better than the other 358 air-conditioned buildings.

In such studies, different methods to evaluate and ensure thermal comfort to users of hybrid buildings were used. However, there is no thermal comfort method specific to hybrid commercial buildings. This is where this work intends to contribute.

2. Objectives

The main objective of this paper is to identify which method to assess thermal comfort is the most appropriate for use in hybrid commercial buildings located in hot and humid summer climates.

Table 2
Room dimensions for each room index and geometry.

Room index – *K*	Geometry – Width (W):Depth (D)			
	2:1		1:2	
	W (m)	*D* (m)	*W* (m)	*D* (m)
0.8	4.92	2.46	2.46	4.92
5.0	30.75	15.38	15.38	30.75

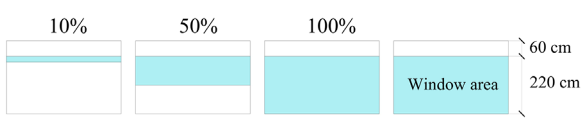

Fig. 3. Window areas.

Table 3
Internal thermal loads.

Room index – K	0.8	5.0
LPD (W/m^2)	13.9	8.1
Occupation (m^2/person)	14.7	
Metabolic activity (W/m^2)	65	
Equipment (W/m^2)	9.7	

3. Method

The work is based on computer simulations of room models of office buildings located in hot and humid summer climate using EnergyPlus 6.0. Natural ventilation simulations were performed and the results were analysed by different methods to assess thermal comfort. Based on this, control schedules of hybrid ventilation (natural ventilation and air-conditioning) were defined considering the heat discomfort limits imposed by the methods to assess thermal comfort. Air-conditioning simulations were not performed as they are not needed for this study.

3.1. The city

The chosen city was Florianópolis, located in the state of Santa Catarina, southern Brazil. The latitude, longitude and altitude of Florianópolis can be seen in Table 1. Fig. 1 shows the minimum, maximum and average monthly outdoor air temperature, while Fig. 2 shows the average monthly outdoor air relative humidity and absolute humidity for Florianópolis. The TRY (Test Reference Year) climate file of Florianópolis [24] was used for the simulations in EnergyPlus.

3.2. Simulation models of office rooms

The models of office rooms are considered to have adiabatic ceiling, floor and interior walls, because what is under assessment is the behaviour of a single model (cell) and not the whole building. All models were considered without barriers or restrictions to air movement. The sizes of the models were based on manuals of illumination (lighting design criteria) and on the work of Ghisi [25], which in turn are based on the room index (K) defined by Eq. (1). The overall height of the rooms was taken as 2.80 m and the working surface as 0.75 m above floor level (*h* is

Table 4
Properties of the building components.
Source: Based on Santana [26].

Element	Material	Roughness	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Thickness (m)	Total thickness (m)
Walls	Plastering mortar	Rough	1.15	2000	1000	0.025	0.200
	Ceramic 6-hole brick	Rough	0.90	1600	920	0.150	
	Plastering mortar	Rough	1.15	2000	1000	0.025	
Floor	Concrete slab	Rough	1.75	2200	1000	0.150	0.185
	Plastering mortar	Rough	1.15	2000	1000	0.025	
	Ceramic floor	Rough	0.90	1600	920	0.010	
Ceiling	Ceramic floor	Rough	0.90	1600	920	0.010	0.185
	Plastering mortar	Rough	1.15	2000	1000	0.025	
	Concrete slab	Rough	1.75	2200	1000	0.150	
Door	Wood	Smooth	0.15	614	2300	0.030	0.030

Table 5
Properties of the glass.
Source: Based on EnergyPlus/datasets [27].

	Thickness (m)	Transmittance		Reflectance (front and back side)		Emissivity (front and back side)	Conductivity (W/m K)
		Solar	Visible	Solar	Visible		
Glass	0.006	0.775	0.881	0.071	0.08	0.84	0.9

equal to 2.05 m).

$$K = \frac{WD}{(W+D)h} \quad (1)$$

where W is the overall width of the room (m), D is the overall depth of the room (m) and h is the mounting height between the working surface and the ceiling (m).

In order to evaluate the influence that different geometries have on the thermal behaviour of the models, two geometries in the proportions (Width:Depth) of 2:1 and 1:2 were analysed. For each geometry, two room sizes were analysed as shown in Table 2. In each model, window areas of 10, 50 and 100%, and two building orientations of the glazed façade were analysed, i.e., south and west. The window area is the total area of the façade that can be glazed. The window is located below a 60 cm beam and has the width of the façade, as shown in Fig. 3.

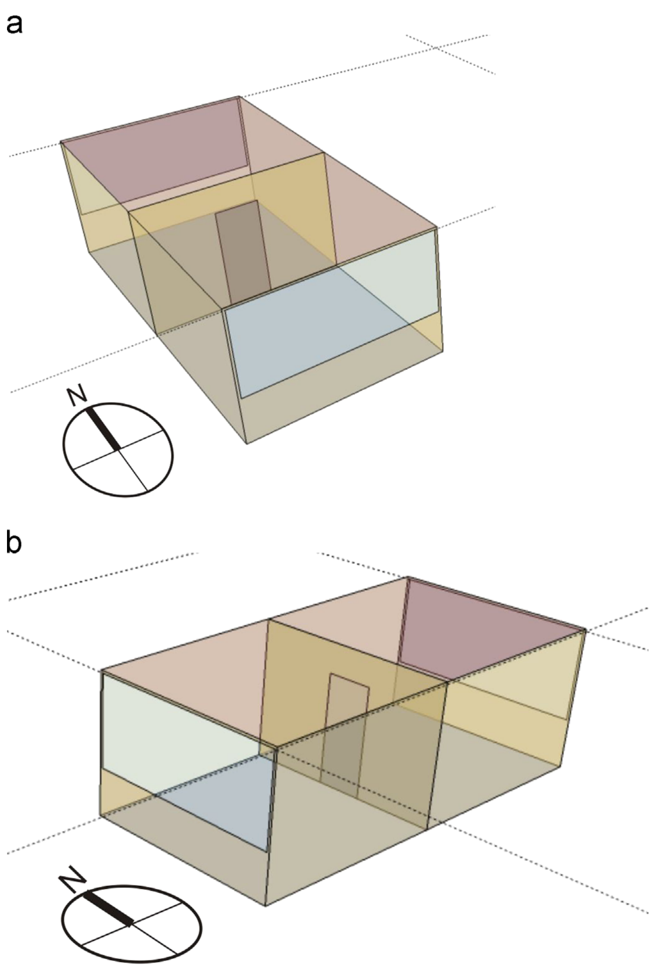

Fig. 4. Examples of simulation models of natural ventilation. (a) Model 1: North–South; (b) Model 2: East–West.

3.3. Simulation parameters

The lighting power density was determined for each room based on a lighting design, which was performed by using the lumen method (Table 3). Fluorescent tube lamps (TL5-28W-HE/840) and recessed luminaries (TBS262) were used.

The other internal loads are also shown in Table 3. These loads were considered during occupation of the building (8am–6pm, Monday–Friday). The occupation and the equipment consumption are based on the work of Santana [26], developed for 35 commercial buildings located in Florianópolis. The metabolic activity value was taken from ANSI/ASHRAE Standard 55 [22].

The building components are also based on the work of Santana [26], with the exception of glass that is based on the database of EnergyPlus [27]. Table 4 shows the building components of walls, ceiling, floor and door; and Table 5 presents the properties of the glass adopted for simulations.

3.4. Simulation of natural ventilation

The simulation of natural ventilation was performed using the Airflow Network model, multi-zone and the wind pressure coefficients were calculated by the EnergyPlus. This decision was based on studies of thermal performance of buildings in two Brazilian cities: Florianópolis and Campo Grande [28,29]. The studies were carried out using EnergyPlus for the simulation of natural ventilation. The authors used several wind pressure coefficients calculated by different means (EnergyPlus, TNO Cp Generator, CpCalc, Tokyo Database). It was concluded that for the same building geometry the different means of calculation show low influence (less than 3%) in the thermal performance of the building, evaluated by cooling degree-hours. It was also concluded that EnergyPlus presented intermediate results among the methods used.

The simulation was performed for two rooms at a time, according to Fig. 4. In model 1 the rooms are North–South oriented while in model 2 they are East–West oriented. This was done because the Airflow Network is a simulation model that requires more than one zone to create a ventilation network. Fig. 4 also shows an interior door separating the rooms; such door measures 0.9×2.2 m^2.

The air mass flow coefficients and exponents when opening is closed are presented in Table 6. Table 6 also shows the discharge coefficients of openings used for natural ventilation simulations.

The windows are operable and the control strategy adopted is based on temperature. This means that the windows were opened (in each hour of the whole year) when three requirements were satisfied: (1) the zone temperature was greater than the outdoor temperature, (2) the zone temperature was greater than the

Table 6
Parameters for natural ventilation simulation.
Source: Based on Liddament [30].

Field Component description	Windows Metal window, 1 leaf – horizontal sliding	Doors Interior wood pivot door, 1 leaf
Air mass flow coefficient when opening is closed (kg/s m)	0.00010	0.00204
Air mass flow exponent when opening is closed (dimensionless)	0.66	0.59
Numbers of sets of opening factor data	2	2
Opening factor 1 – Opening closed (dimensionless)	0	0
Discharge coefficient for opening factor 1 (dimensionless)	0.001	0.001
Opening factor 2 – Opening opened (dimensionless)	1	1
Discharge coefficient for opening factor 2 (dimensionless)	0.6	0.65

setpoint temperature of natural ventilation and (3) the schedule control of natural ventilation allowed ventilation (i.e., schedule control of natural ventilation was equal to 1), from Monday to Friday. The setpoint temperatures for natural ventilation were 22 °C (autumn and winter, from March 21 to September 20) and 20 °C (spring and summer, from September 21 to March 20), as recommended by Sorgato [28] for Florianópolis climate. Two situations were simulated: with the interior door closed and with the interior door opened throughout the simulation period.

3.5. Schedule control of hybrid ventilation

From the results of simulations of natural ventilation and in order to incorporate the hybrid ventilation in a future work, control schedules of air-conditioning and control schedules of natural ventilation were created using spreadsheets. The control schedule of air-conditioning shows when the air-conditioning would be necessary in case the hybrid ventilation strategy is implemented. This schedule is the opposite of the control schedule of natural ventilation, i.e., when natural ventilation is allowed, the use of air-conditioning is not allowed and vice versa. These schedules were performed on an hourly basis for the whole year. For each hour, if the value in the spreadsheets for the control schedule of natural ventilation was zero (0) then the use of air-conditioning would be necessary, without natural ventilation; if the value was one (1) natural ventilation would be used with no use of air-conditioning. The order of these values (0 or 1) are inverted in the control schedule of air-conditioning, i.e., zero (0) means that the natural ventilation can be used with no use of air-conditioning and one (1) means that the use of air-conditioning will be necessary, without natural ventilation.

The objective of these schedules is to control the hybrid ventilation strategy considering the thermal comfort. Thus, in order to determine the control schedule of hybrid ventilation, i.e., the control schedule of air-conditioning and the control schedule of natural ventilation, it was first necessary to define which method to assess thermal comfort is the most appropriate for use in hybrid commercial buildings located in the Florianópolis climate.

It is important to emphasise that control schedules of air-conditioning were obtained in order to compare them with the pattern of air-conditioning use in Florianópolis; however, air-conditioning simulations were not performed.

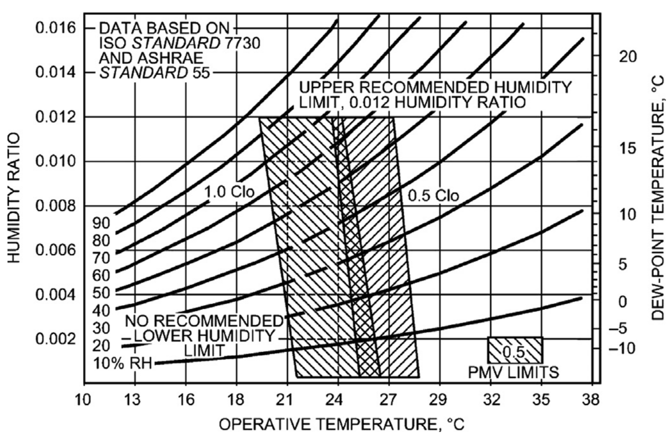

Fig. 5. Acceptable range of operative temperature and humidity for spaces. *Source*: ASHRAE Handbook Fundamentals [33].

3.6. Methods to assess thermal comfort

Three methods were evaluated. These methods were chosen because they have been widely used in scientific researches and by thermal comfort professionals:

(1) Method for determining acceptable thermal conditions in occupied spaces (ASHRAE 55 [22]). This method was originally developed for air-conditioned spaces [31]. But, the way it was published in ASHRAE 55 [22], it is accepted as applicable to all conditions in occupied spaces [21];
(2) Method for determining acceptable thermal conditions in naturally ventilated spaces (ASHRAE 55 [22]);
(3) Method of Givoni for hot and humid climates [32].

In Florianópolis, air-conditioning is not used for heating offices in commercial buildings [26], so for the determination of the schedules of hybrid ventilation in all situations, it was only necessary to determine when the air-conditioning would be required in cooling mode. Thus, only the upper limits (heat discomfort) imposed by the methods to assess thermal comfort were considered.

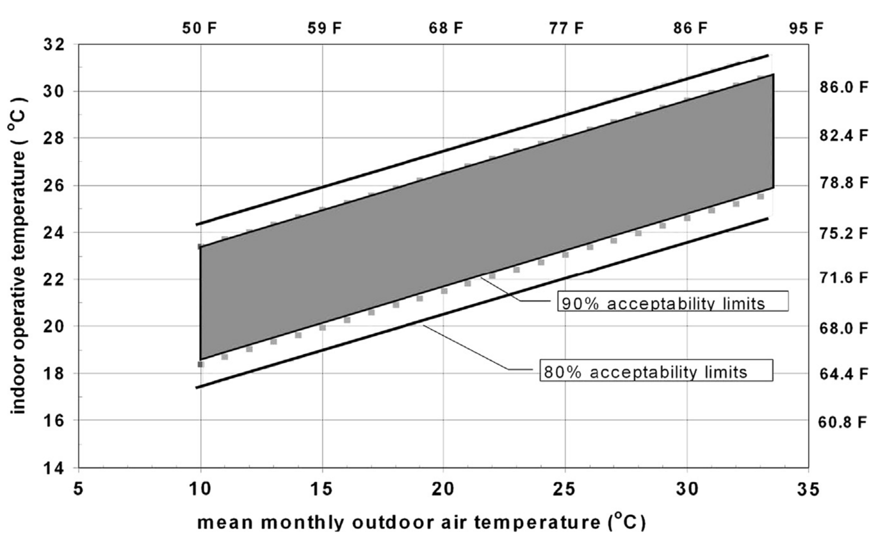

Fig. 6. Acceptable operative temperature ranges for naturally ventilated spaces. *Source*: ASHRAE 55 [22].

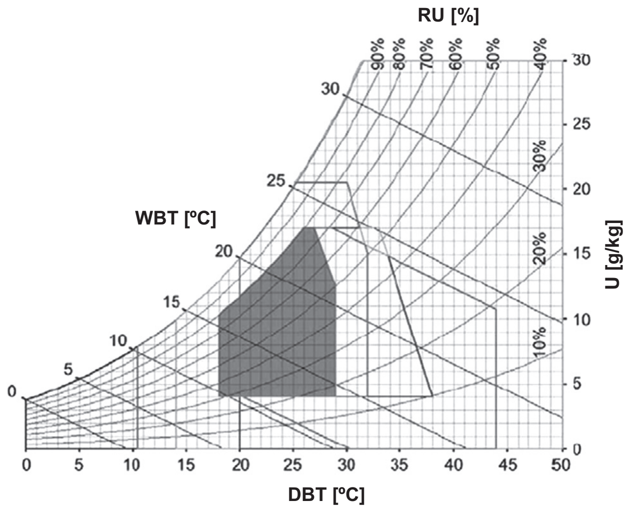

Fig. 7. Thermal comfort zone for hot and humid climates. Based on Givoni [32].

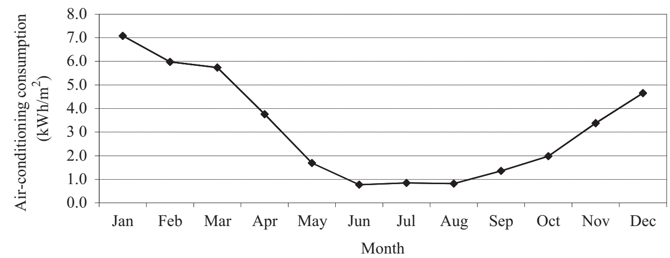

Fig. 8. Electricity consumption of the predominant typology of commercial buildings in Florianópolis. Adapted of Santana [26].

3.6.1. *ASHRAE 55 method for determining acceptable thermal conditions in occupied spaces*

The ASHRAE 55 method for occupied spaces can be seen in Fig. 5, where the acceptable range of operative temperature and absolute humidity for 80% of acceptability can be seen.

The simulations output on an hourly basis considering natural ventilation (operative temperature and absolute humidity) were compared with the acceptable range of temperature and humidity of ASHRAE 55. Hence, Monday–Friday, from 8am to 6pm, when the values of temperature and humidity were higher than the acceptable range, air-conditioning would be necessary. As ASHRAE 55 does not show the values that define the acceptable range of temperature and humidity (except for the upper limit of absolute humidity -0.012 kg/kg), these values were estimated by using Eqs. (2) and (3).

$$U_r = -0.0125T_o + 0.3520 \tag{2}$$

$$U_l = -0.0071T_o + 0.1534 \tag{3}$$

where U_r is the absolute humidity for the right side zone of Fig. 5 (kg/kg); U_l is the absolute humidity for the left side zone of Fig. 5 (kg/kg); T_o is the indoor operative temperature (°C).

3.6.2. *ASHRAE 55 method for determining acceptable thermal conditions in naturally ventilated spaces*

ASHRAE 55 also provides an optional method that can be applied to naturally ventilated spaces, in which occupants have some control over the openings. According to this method, the space could not have a mechanical cooling system. However, this work deals with hybrid buildings operating in parts of the year with natural ventilation through operable windows. Moreover, it is considered that users of this typology of building tolerate greater temperature variations than those who occupy air-conditioned buildings. This finding was demonstrated by the ASHRAE RP-884 [31]. Thus, this method was also applied in this research.

Fig. 6 shows the range of acceptability (80% and 90%) of operative temperature as a function of average monthly outdoor air temperature, for naturally ventilated spaces. Fig. 6 was developed by de Dear and Brager [21] based on comfort operative temperature (Eq. (4)), derived from ASHRAE RP-884 [31]. Based on this equation, de Dear and Brager [21] established a range of operative temperature of ± 2.5 °C for 90% of acceptability and ± 3.5 °C for 80% of acceptability.

$$T_{\text{comf}} = 0.31.T_{\text{mout}} + 17.8 \tag{4}$$

where T_{comf} is the comfort operative temperature (°C); T_{mout} is the mean monthly outdoor air temperature (°C).

Using the results of indoor operative temperatures, on an hourly basis, and the average monthly outdoor air temperatures it was possible to determine when the indoor temperatures were higher than the range of acceptability. In such a case, air conditioning would be necessary.

3.6.3. *Givoni's method*

Givoni [32] developed a method to assess thermal comfort in hot and humid climates. This method was based on expected indoor temperatures in naturally ventilated buildings. As in ASHRAE 55 for naturally ventilated spaces, the building operates with hybrid ventilation (operating in parts of the year with natural ventilation) and the climate in study is hot and humid (in summer), this method was also applied in this research.

Indoor dry-bulb temperature, absolute humidity and relative humidity, obtained from the natural ventilation simulations, were compared with the upper accepted limits of thermal comfort zone of Givoni's chart (Fig. 7). Thus, the upper accepted limit of relative humidity is 80%. Up to 27 °C of dry-bulb temperature, the upper accepted limit of absolute humidity is 17 g/kg. Between 27 °C and 29 °C of dry-bulb temperature the upper accepted limit of absolute humidity is given by Eq. (5), which was obtained based on the Givoni's chart. Above such limits air conditioning would be necessary.

$$U = -2.25\text{DBT} + 77.75, \quad 27\,°C < \text{DBT} < 29\,°C \tag{5}$$

where U is the absolute humidity (g/kg); DBT is the dry-bulb temperature (°C).

3.7. *Correlations*

Results obtained from the natural ventilation simulations were plotted on the graphs of each of the three methods to assess thermal comfort. As for Givoni's method, the hourly values of dry-bulb temperature, absolute humidity and relative humidity for the whole year were plotted on the Givoni's chart using the Analysis Bio 2.2 programme [34].

The values 0 or 1 obtained from the control schedules of air-conditioning developed for each room were added throughout the year. Such sum gave the total number of hours per year that the air-conditioning was turned on in cooling mode (referred to in this paper simply as number of hours), for each method and for each room. This number of hours represents the number of hours of heat discomfort. Thus, the number of hours was compared among each evaluation method on daily basis for the whole year. Graphs with the number of hours for each method and for the same room were developed to ease the comparison.

Correlations between the total number of hours in the year in which the air-conditioning will be necessary, and the number of hours of use of air-conditioning of the predominant typology of commercial building in Florianópolis, as defined by [26], were

performed. Santana [26] defined a predominant typology from an analysis of 35 office buildings located in Florianópolis. Analyses were performed in relation to the constructive characterisation and to the occupation pattern and equipment use. The room area of the predominant typology from the study of Santana [26] is 88 m^2 (geometry 1:1.4) and the peak power of the air-conditioning in this room is 3.51 kW. Through simulation of this predominant typology in EnergyPlus, Santana [26] obtained the air-conditioning consumption throughout the year (Fig. 8).

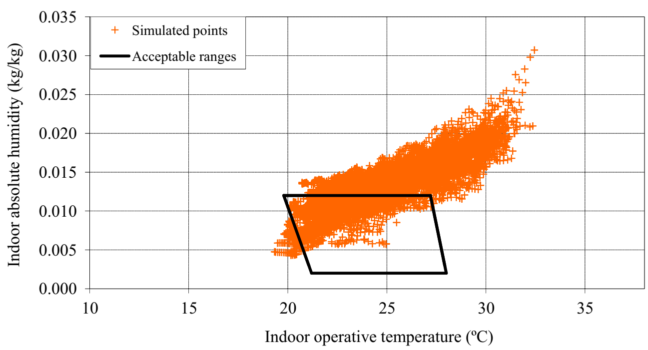

Fig. 9. Results of the simulation of natural ventilation for the model with geometry of 1:2, room index equal to 0.8, 10% of window area, west orientation and the interior door closed – Method of ASHRAE 55 for occupied spaces [22].

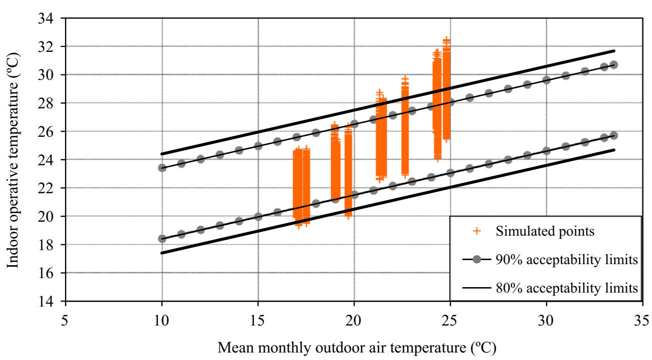

Fig. 10. Results of the simulation of natural ventilation for the model with geometry of 1:2, room index equal to 0.8, 10% of window area, west orientation and the interior door closed – Method of ASHRAE 55 for naturally ventilated spaces [22].

The number of hours of air-conditioning use was calculated based on the EnergyPlus file of the predominant typology of commercial buildings of Santana's study [26]. The air-conditioning consumption on an hourly basis was obtained from such a file. The total number of hours per year that the air-conditioning was turned on was obtained by adding each hour of air-conditioning use throughout the year.

Thus, correlations were performed between: (a) the number of hours of air-conditioning use obtained from the three methods and the outdoor variables, (b) the number of hours of air-conditioning use obtained from the three methods and the number of hours of air-conditioning use of the predominant typology of commercial buildings in Florianópolis. Coefficients of determination were obtained to evaluate the correlations and the results were shown in graphs. The bisection was also drawn in each of these graphs in order to consider the real behaviour of air-conditioning use. Thus, methods with results above the bisector consume more air-conditioning electricity than a typical commercial building in Florianópolis and may not be adequate to be used with the hybrid ventilation strategy. On the other hand, methods with results below the bisector consume less air-conditioning electricity than a typical commercial building in Florianópolis and are more adequate to be used with the hybrid ventilation strategy.

The decision on the most adequate method to assess thermal comfort to be used in hybrid commercial buildings was made from such comparisons and from the pattern of air-conditioning use, as defined by Santana [26], Moreira [35] and Coelho [36]. The highest use of air-conditioning for cooling office buildings located in Florianópolis occurs from December to March, and there is scarcely any use from June to August [26,35,36].

4. Results

4.1. Simulation of natural ventilation

The results of the simulations of natural ventilation were plotted on the three different thermal comfort methods discussed in this work, for the four models, with three window areas and two solar orientations. Figs. 9–11 show some of these results for

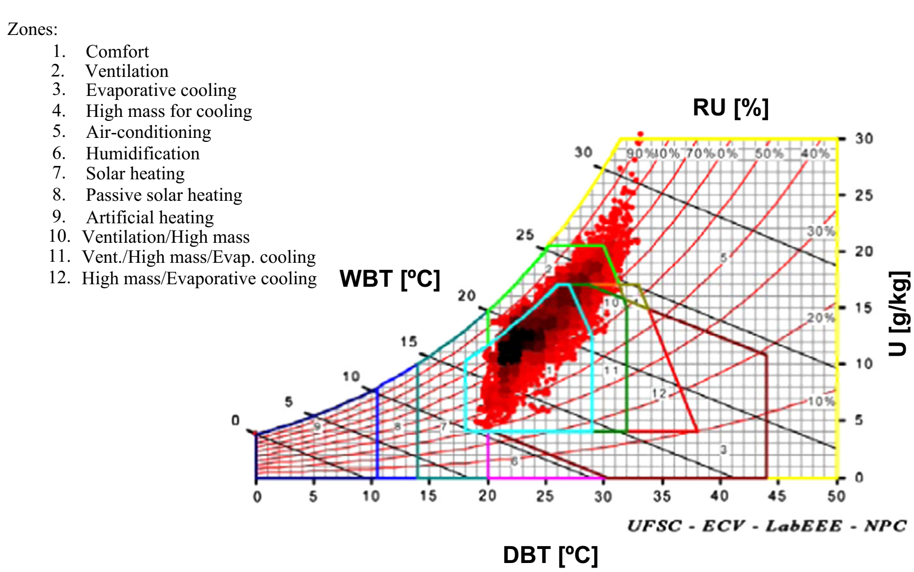

Fig. 11. Results of the simulation of natural ventilation for the model with geometry of 1:2, room index equal to 0.8, 10% of window area, west orientation and the interior door closed – Method of Givoni.

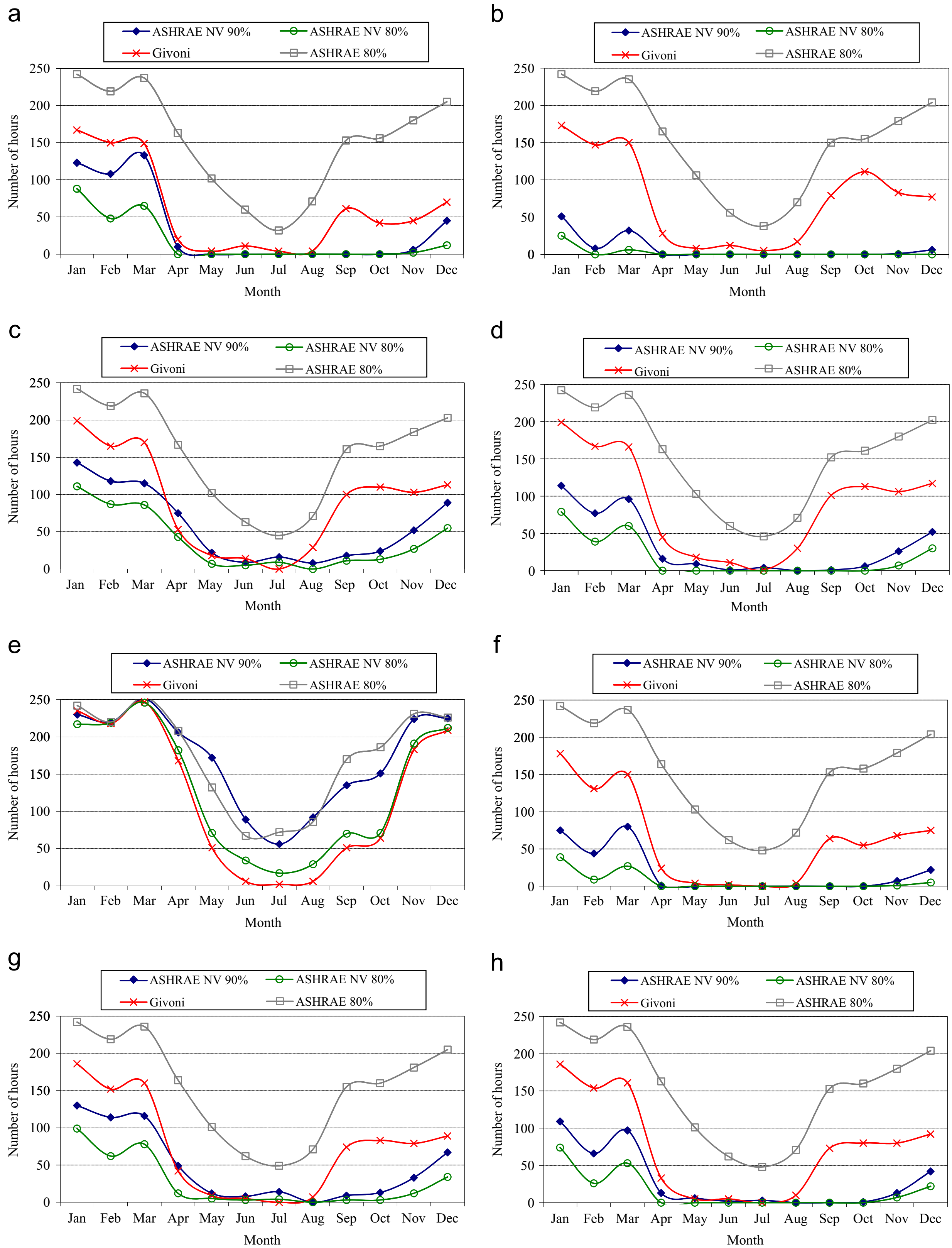

Fig. 12. Number of hours of use of air-conditioning to the model with interior door closed, geometry of 2:1, room index equal to 0.8 and 5.0, west and south orientations and window areas of 10 and 100%. (a) $K=0.8$, west orientation, 10% of window area; (b) $K=0.8$, south orientation, 10% of window area; (c) $K=0.8$, west orientation, 100% of window area; (d) $K=0.8$, south orientation, 100% of window area; (e) $K=5.0$, west orientation, 10% of window area; (f) $K=5.0$, south orientation, 10% of window area; (g) $K=5.0$, west orientation, 100% of window area; (h) $K=5.0$, south orientation, 100% of window area.

the model with geometry of 1:2, room index equal to 0.8, 10% of window area, west orientation and interior door closed. Fig. 9 differs from Fig. 5 because in the latter the upper limit of absolute humidity is 0.016 kg/kg. However, in order for the high values of humidity to be seen (greater than 0.030 kg/kg), the ordinate axis was expanded. Thus, the look of the graph changed, but the

Table 7
Number of hours of use of air-conditioning throughout the year for each method to assess thermal comfort.

Method	Window area (%)	Geometry							
		1:2				2:1			
		$K=0.8$		$K=5.0$		$K=0.8$		$K=5.0$	
		West	South	West	South	West	South	West	South
		Number of hours with interior door closed							
ASHRAE NV 90	10	741	217	**839**	600	425	98	**2051**	229
	50	421	249	**772**	600	502	283	596	409
	100	510	288	514	352	689	402	565	352
ASHRAE NV 80	10	439	64	455	302	215	31	*1559*	81
	50	219	108	418	302	290	157	318	207
	100	283	158	257	171	454	215	315	182
ASHRAE 80	10	1840	1842	1863	1854	1820	1819	2093	1841
	50	1840	1846	1851	1850	1842	1842	1848	1843
	100	1842	1841	1844	1837	1858	1835	1845	1839
GIVONI	10	782	683	809	743	727	890	1440	755
	50	830	840	747	709	947	944	765	763
	100	973	986	793	790	1074	1074	886	879
Method	W. Area (%)	Number of hours with interior door opened							
ASHRAE-NV 90	10	228	98	**812**	506	185	73	**1401**	215
	50	298	183	**753**	533	433	241	603	397
	100	454	258	520	351	677	390	570	358
ASHRAE NV 80	10	66	17	434	242	66	21	937	80
	50	149	67	404	266	237	130	330	195
	100	256	143	263	175	443	208	318	186
ASHRAE 80	10	1836	1832	1849	1846	1826	1821	1892	1842
	50	1839	1831	1846	1849	1843	1833	1845	1845
	100	1841	1835	1845	1843	1857	1827	1845	1838
GIVONI	10	699	800	808	687	866	1006	1086	761
	50	941	999	729	671	1011	1044	778	752
	100	1017	1042	799	791	1075	1083	884	891

acceptable ranges of temperature and humidity did not. Fig. 11 also shows the bioclimatic zones as described in Givoni [32]; zone 1 is the thermal comfort zone. As it can be observed, for the same model, a greater number of hours are out of the thermal comfort zone for the methods of ASHRAE 55 for occupied spaces (64.5% of discomfort) and Givoni (23.1% of discomfort), in relation to the ASHRAE 55 alternative method (10.6% of discomfort for 80% of acceptability and 22.1% of discomfort for 90% of acceptability). This difference occurs because these two methods consider humidity, which is high in the climate under study. It is emphasised that the method of ASHRAE 55 for occupied spaces presented the highest percentages of discomfort by setting an upper acceptable humidity limit very low (0.012 kg/kg). This trend remained the same for all models. However, these results are shown for the whole year (8760 h). Thus, control schedules were developed to perform a comparison only during the occupation hours of the building (8am–6pm, Monday to Friday).

4.2. Control schedules of air-conditioning

Monthly results of the sums of the control schedules of air-conditioning developed for one geometry, two room indices, two window areas, two orientations, with interior door closed, by the methods of ASHRAE 55 for occupied spaces (ASHRAE 80%), ASHRAE 55 for naturally ventilated spaces with 80% of acceptability (ASHRAE NV 80%) and with 90% of acceptability (ASHRAE NV 90%), and Givoni, can be seen in Fig. 12.

It is clear that (a) the trends obtained for the method of ASHRAE 55 for occupied spaces is different from the pattern of air-conditioning use in Florianópolis during winter (June, July and August); (b) the trends obtained for the other methods are similar to the pattern of air-conditioning use in Florianópolis (with some exceptions); (c) the number of hours obtained for the method of ASHRAE 55 for naturally ventilated spaces (90% of acceptability) and Givoni were similar; even for models with the interior door opened.

A different trend can be noted in Fig. 12(e). In the geometry 2:1, room index equal to 5.0 and west orientation, there is more solar thermal load than in the south. In such a model with 10% of window area, natural ventilation was not effective, as it led to the greatest number of hours of air-conditioning use for each method.

The values of average monthly temperature (Fig. 1), average monthly absolute humidity (Fig. 2) and average monthly relative humidity reached their highest levels from January to March. An exception occurred in September, when there was a peak in the relative humidity value. These facts are closely related to the number of hours that also reached their highest values (Fig. 12). From April to August, the temperature and the humidity are lower, resulting in a smaller number of hours of air-conditioning use. From August onwards, the monthly average temperatures and

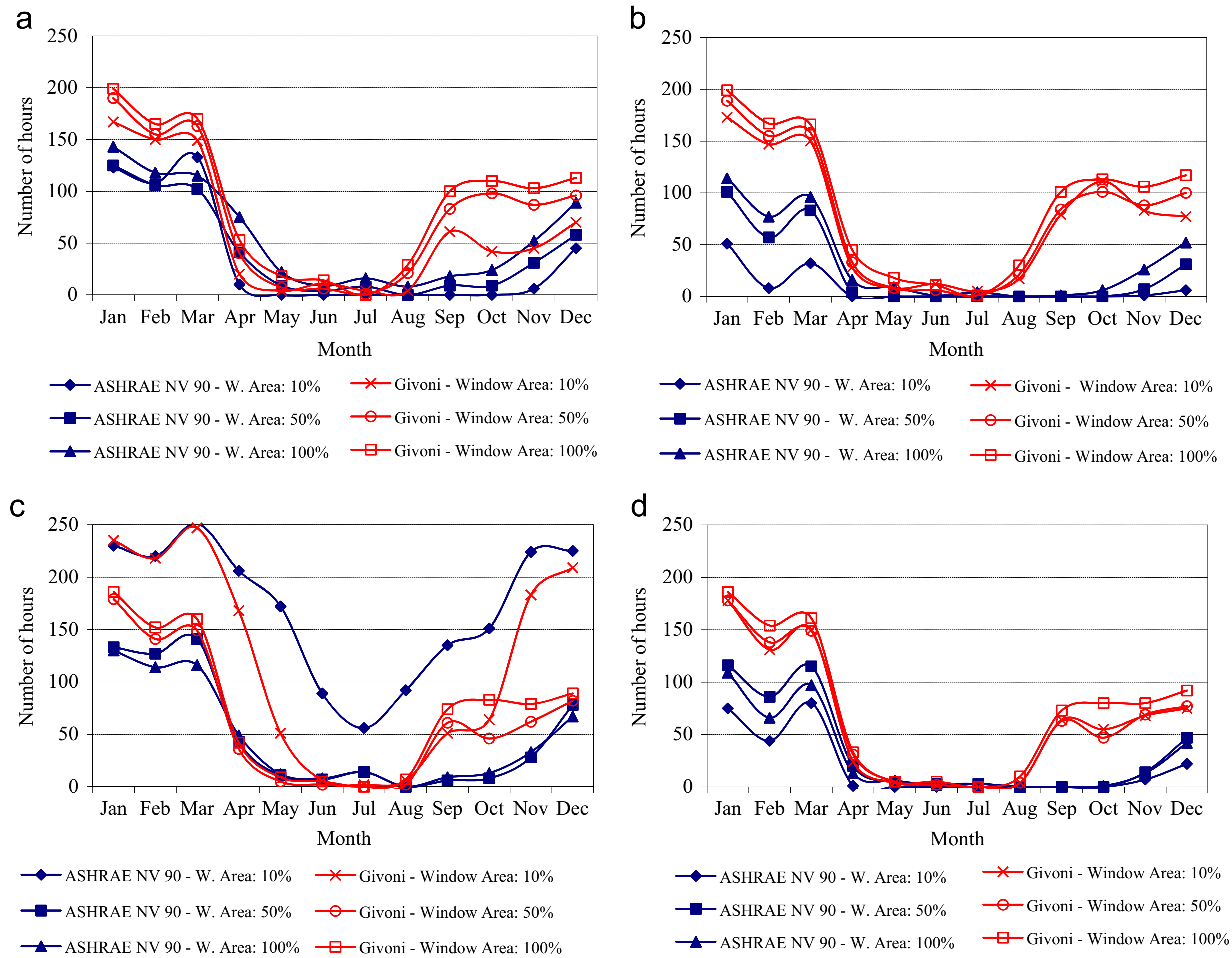

Fig. 13. Number of hours of use of air-conditioning to the model with geometry of 2:1, room index equal to 0.8 and 5.0, window areas of 10, 50 and 100%, interior door closed. (a) $K=0.8$, west orientation; (b) $K=0.8$, south orientation; (c) $K=5.0$, west orientation; (d) $K=5.0$, south orientation.

absolute humidity increased similarly. On the other hand, the monthly average relative humidity presented a different tendency, especially from September to December, in which, unlike the temperature and absolute humidity, showed a downward trend.

The number of hours of air-conditioning use along the year was also obtained for all models, for each method to assess thermal comfort, with interior door opened and closed, as shown in Table 7. It can be noticed that, in general, the number of hours is greater for models with room index equal to 5.0 than for room index equal to 0.8. As for Givoni's method, the opposite trend was observed in most situations. Another factor is that the increase of window area increases the internal thermal load of the room. Thus, the awaited trend is that there would be a greater number of hours of air-conditioning use. In general, this awaited trend was observed for Givoni's method. However, for some cases in the method of ASHRAE 55 for naturally ventilated spaces this trend was observed, but for other cases the opposite pattern occurred (the number of hours decreased). The increase in the window area did not significantly affect the number of hours of air-conditioning use for the method of ASHRAE 55 for occupied spaces.

Thus, as shown in Table 7, the number of hours per year obtained from the method of ASHRAE 55 for occupied spaces is much greater than the other methods, for all cases. This fact is due to the narrow limits established by this standard, to guarantee thermal comfort. Even in winter (June, July and August), as shown in Fig. 12, due to high humidity, typical of the climate of Florianópolis, there would be a significant use of air-conditioning for cooling. This trend was the same for all models studied in this work. Thus, this method was considered not suitable to be applied to environments with high humidity and for the hybrid ventilation strategy proposed in this paper.

The smallest numbers of hours were obtained for the method of ASHRAE 55 for naturally ventilated spaces (80% of acceptability) with the exception of one model (marked italics in Table 7) which resulted in a greater number of hours than Givoni's method. By this method, in December, the number of hours of air-conditioning use was close to zero. Thus, the method of ASHRAE 55 for naturally ventilated spaces (80% of acceptability) did not prove suitable for use in the climate of Florianópolis.

As a result, the methods of Givoni and ASHRAE 55 for naturally ventilated spaces (90% of acceptability) remained to be assessed in detail. These methods showed a behaviour that met the pattern of use of air-conditioning in Florianópolis and are rather similar to each other. In general, the number of hours by Givoni's method was greater than the alternative method of ASHRAE 55 with 90% of acceptability, with the exception of three models (marked bold in Table 7). The number of hours throughout the year for all models was analysed to identify over which months these differences occur and why they occur. Fig. 13 shows the results of number of hours obtained from the methods of Givoni and ASHRAE 55 for naturally ventilated spaces (90% of acceptability), for window areas of 10, 50 and 100%, for the model with geometry of 2:1, room index equal to 0.8 and 5.0 and interior door closed.

From Fig. 13 it can be seen that the greatest differences between the methods occur from September to November.

Table 8
Maximum and minimum coefficient of determination for each method to assess thermal comfort.

Variable	R^2 value	ASHRAE NV 90%	ASHRAE NV 80%	ASHRAE 80%	GIVONI
Air temperature	Maximum	0.94	0.93	0.93	0.95
	Minimum	0.46	0.29	0.85	0.73
Relative humidity	Maximum	0.18	0.18	0.16	0.36
	Minimum	0.01	0.03	0.09	0.04
Absolute humidity	Maximum	0.94	0.94	0.90	0.94
	Minimum	0.53	0.35	0.79	0.81

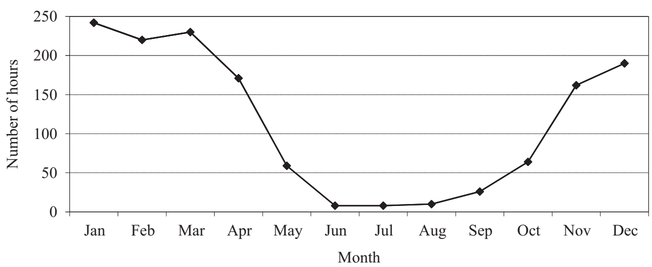

Fig. 14. Number of hours per month of use of air-conditioning calculated for the predominant typology of commercial buildings. Based on Santana [26].

The number of hours obtained from the method of Givoni almost did not differ among the solar orientations. On the other hand, from the method of ASHRAE 55 for naturally ventilated spaces (90% of acceptability), the number of hours for west orientation is greater than south orientation. This difference occurs because the indoor operative temperatures and the indoor air temperatures for south orientation are lesser than west orientation. Thus, the method of ASHRAE 55 for naturally ventilated spaces (90% of acceptability) leads to a smaller number of hours for the south orientation than the west orientation. This happens because this method considers only the indoor operative temperature. In contrast, the method of Givoni considers the indoor humidity, and as a consequence, if the indoor air temperature is low but the humidity is high (the indoor absolute humidity does not vary significantly between the orientations) the air-conditioning will be turned on. This behaviour was observed in all models, with the interior door either opened or closed.

According to a research conducted by Coelho [36], there is little variation in energy consumption between west and south orientations in commercial buildings located in Florianópolis. This research was based on real data of energy consumption for 19 commercial buildings. Coelho [36] correlated the energy consumption with construction characteristics of such buildings and obtained energy consumptions of 79.3 kWh/m^2 yr for south orientation and 77.6 kWh/m^2 yr for west orientation.

The method of ASHRAE was developed based on a database involving different climates on different continents. The countries analysed were England, Thailand, United States, Indonesia, Canada, Australia, Pakistan, Greece and Malaysia [31]. The relative humidity in these countries varies considerably between summer, 55.8%, and winter, 32.8% [31]. This is not observed in Florianópolis, where monthly average relative humidity ranges from 88.7% to 82.1%, i.e., relative humidity is much higher than observed in those countries. Average relative humidity in the models simulated in this work ranged from 78.2% in summer to 66.5% in winter, also higher than those that originated the ASHRAE method. In humid climates, a humidity limit must be implemented in the adaptive comfort method of ASHRAE 55 for naturally ventilated spaces to prevent moisture problems (condensation degradation of materials and biological contamination) [12]. Also Fanger and Toftum [13] pointed out that one of weaknesses of the adaptive model of ASHRAE 55 is the fact that the method does not consider the humidity for its application (environmental parameter that has a well-known impact on thermal comfort).

Thus, the method of Givoni seems to be the most suitable to the climate under study. However, the following sections will show some other analyses to verify whether such method is really suitable.

4.3. Correlation between the number of hours and the outdoor environmental variables

The number of hours of air-conditioning use obtained from the three methods was correlated with the outdoor environmental variables. For all models, the maximum and minimum R^2 for the different methods can be seen in Table 8.

It can be noticed that the method of ASHRAE 55 for occupied spaces originated the greatest R^2 and the method of ASHRAE 55 for naturally ventilated spaces (80% of acceptability) the smallest.

In general, results show that the use of the air-conditioning depends on temperature and absolute humidity (high R^2), but also depends on relative humidity (low R^2, but greater than zero). This shows the importance of considering the effects of humidity in the evaluation of thermal comfort.

4.4. Correlation between the number of hours and the number of hours of the predominant typology

The number of hours of air-conditioning use obtained from the three methods was also correlated with the number of hours of the predominant typology of commercial building located in Florianópolis, calculated using the EnergyPlus file of Santana [26].

The monthly number of hours of air-conditioning use calculated for the predominant typology of commercial buildings is presented in Fig. 14. Even in winter, there are hot days with high solar radiation, resulting in the use of the air-conditioning for cooling.

The greatest number of hours of air-conditioning use occurs between January and March. From March on, the number of hours decreases, being slightly above zero between June and August. Between August and December there is a gradual increase in the number of hours.

Fig. 15 shows the correlations and the R^2 for the models with interior door closed, geometry of 2:1, room index equal to 0.8, west and south orientations and window areas of 10, 50 and 100%. Fig. 15 also contains the bisector. Based on such graphs, it was verified which method had results below (the method is considered adequate) or above (the method is considered not adequate) the bisector. The R^2 for the method of ASHRAE 55 for occupied spaces ranged from 0.60 to 0.88. The method of ASHRAE 55 for naturally ventilated spaces (80% of acceptability) presented the worst R^2; the maximum value was 0.89 and the minimum value was 0.25.

Once again, the methods of Givoni (R^2 between 0.59 and 0.99) and ASHRAE 55 for naturally ventilated spaces with 90% of acceptability (R^2 between 0.40 and 0.92) showed similar results. This confirms the previous discussions. However, the number of hours of air-conditioning use obtained with the method of ASHRAE 55 for naturally ventilated spaces (90% of acceptability) sometimes presents very low values for December, which is not consistent with the pattern of air-conditioning use observed in Florianópolis.

In general, Givoni's method was the one with results closer and below to the bisector for all cases with either interior door opened or closed. The method of Givoni also presented the most consistent air-conditioning consumption compared to the pattern of air-conditioning use in Florianópolis. The ASHRAE 55 method for

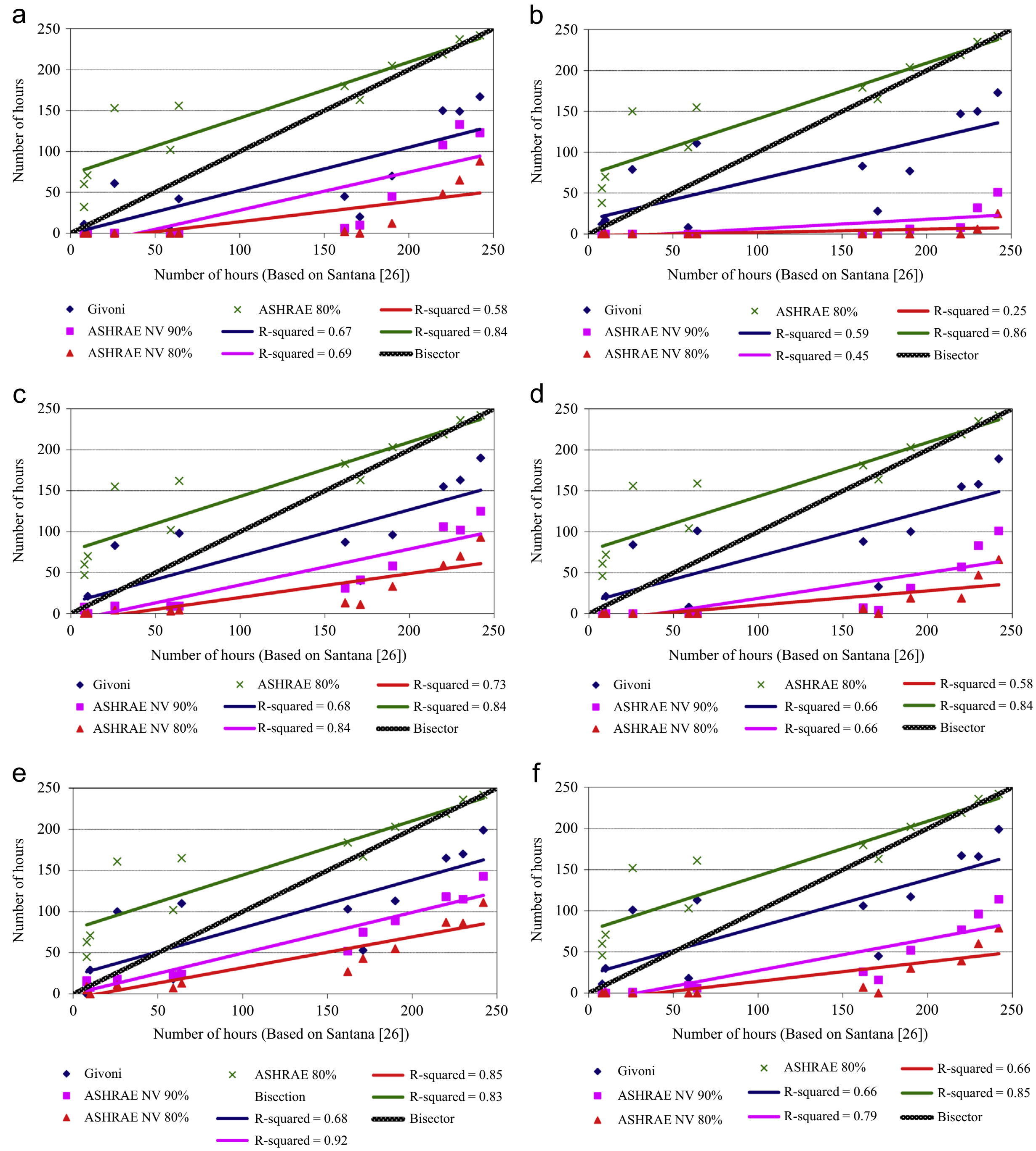

Fig. 15. Correlation between number of hours of use of air-conditioning and the number of hours of use of air-conditioning estimated from predominant typology of commercial buildings to the model with interior door closed, geometry of 2:1, room index equal to 0.8, west and south orientations and window areas of 10, 50 and 100%. (a) West orientation, 10% of window area; (b) South orientation, 10% of window area; (c) West orientation, 50% of window area; (d) South orientation, 50% of window area; (e) West orientation, 100% of window area; (f) South orientation, 100% of window area.

naturally ventilated spaces (both 90% and 80% of acceptability) and the ASHRAE 55 method for occupied spaces were the ones with results more distant to the bisector in all cases. Thus, for the ASHRAE 55 method for naturally ventilated spaces (both 90% and 80% of acceptability), the straight lines always showed lower values than the values of the bisector, while for ASHRAE 55 method for occupied spaces, the straight lines always showed higher or equal values than those of the bisector.

As the geometry of the predominant typology obtained by Santana [26] is 1:1.4, correlations were made and the bisection was drawn to the geometry of 1:1 (room dimensions of 3.28×3.28 m^2 for room index equal to 0.8 with lighting power density of 15.6 W/m^2; room dimensions of 20.5×20.5 m^2 for room index equal to 5.0 with lighting power density of 8.0 W/m^2), for models with the characteristics presented in this work. The results were similar to those presented by the geometries of 1:2 and 2:1.

Therefore, Givoni's method was considered the most appropriate to be used in climates similar to the one observed in Florianópolis, i.e., hot and humid summer climate.

5. Conclusions

In order to identify which method to assess thermal comfort is the most appropriate for use in hybrid commercial buildings

located in hot and humid summer climates and given that there is not a specific method to assess thermal comfort for such buildings, this research was carried out.

The method proposed herein can be applied anywhere in the world for hybrid commercial buildings since the input simulation parameters are adapted to the local climate of interest. However, the conclusions of this study are limited to hot and humid summer climates.

Through the correlations between the number of hours of air-conditioning use and the outdoor environmental variables, it can be concluded that the use of air-conditioning is very dependent on air temperature and absolute humidity. Indeed, it also depends on relative humidity, but with lesser importance. This emphasises the importance of using a method that considers the humidity effects in the evaluation of thermal comfort, as recommended by Fanger and Toftum [13]. Furthermore, a humidity threshold is necessary to prevent moisture problems in humid climates [12].

Based on results shown in this paper, it can be concluded that the ASHRAE 55 method for occupied spaces is not suitable for application in hybrid commercial buildings located in hot and humid summer climates like observed in Florianópolis, due to the narrow humidity limits set by this standard to guarantee thermal comfort. These limits led to a significant and unrealistic use of air-conditioning for cooling in winter months. The ASHRAE 55 method for naturally ventilated spaces led to very low use of air-conditioning in December (summer), which is not consistent with the pattern of air-conditioning use observed in Florianópolis.

Correlations between the number of hours of air-conditioning use obtained from the simulations and from the predominant typology of commercial buildings located in Florianópolis were performed for each method to assess thermal comfort. By comparing these correlations, it was concluded that the most suitable method for use in hot and humid summer climates was the method of Givoni.

Through this study, the importance of choosing the method to assess thermal comfort for the determination of control schedules of hybrid ventilation depending on the building typology and the climate was assessed. Thus, the use of unrealistic data, leading to excessive or reduced use of air-conditioning is prevented.

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